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POWER QUALITY ENHANCEMENT USING D-STATCOM WITH LCL FILTER FOR DISTRIBUTION SYSTEMS

FIRAS MARWAN FAKHRALDIN[1], JYOTI SHRIVASTAVA[2], MOHAMMED RAMIZ ALMALLAH[3] & ISRAATAWFIK AZIZ[4]

[1]General Directorate of North Distribution Electricity, Ministry of Electricity, Iraq

[2]Department of Electrical Engineering, SHIATS, Allahabad, Uttar Pradesh, India

[3]General Directorate of Electricity Transmission, Northern Ministry of Electricity, Maharashtra, India

[4]College of Science, University of Mosul, Ministry of Higher Education, Mosul, Iraq

ABSTRACT

This paper presents the improvement of voltage sags; harmonic distortion and low power factor by preparing model of Distribution Static Compensator (D-STATCOM) with LCL Passive Filter in distribution system using MATLAB Simulink, then evaluate and analyze the performance of D-STATCOM and LCL filter in distribution system. The model is based on the Voltage Source Converter (VSC) principle. The D-STATCOM injects a current into the system to mitigate the voltage sags. LCL Passive Filter was then added to D-STATCOM to improve harmonic distortion and low power factor. The simulations were performed using MATLAB SIMULINK version R2009b.

KEYWORDS: Distribution Static Compensator, Power Quality, Passive Filter, LCL Filter, Voltage Sags, Current Harmonics

INTRODUCTION

The power sources in conventional power systems must operate at exactly the same frequency and in perfect synchronism. Each generator controls the magnitude of its terminal voltage by the excitation current and the phase angle of this voltage by means of the mechanical torque developed by the turbine. The generators are designed to produce relatively low voltages, and thus the generated power undergoes a number of voltage transformations, from low to high voltage (for efficient power transmission) and from high to medium and low voltage (for economic and safe power distribution). These changes are implemented by power transformers. Within a national grid, the use of a fully interconnected primary transmission system, to which the new power stations are connected, has traditionally been the generally accepted philosophy behind the development of an efficient power system.

The expansion of the primary transmission system was normally continued until the rated switchgear fault level was exceeded. Beyond that point a new primary transmission system, of higher voltage and fault levels, was created, while the previous one continued expanding into several separate (secondary) systems. Each of these secondary transmission systems in turn supplied a number of distribution (normally radial) feeders. So the conventional power grid has traditionally been grouped into three separate parts: generation, transmission and distribution [3]. A modern power distribution system, due to advancement in technology, has found many applications of switching devices such as uninterrupted power supplies, rectifier load, adjustable speed drives, arc furnace, and switched-mode power supply. These non-linear loads in combination with linear loads draw reactive and harmonics power from supply mains which

degrades the power quality (PQ) in distribution network. Conventional PQ mitigation techniques use static capacitors and are highly effective under fixed load conditions.

But it has drawbacks, namely, fixed compensation, bulky size, and may cause resonance with transmission line reactance [1].The changes of voltage, current, and frequency could result in error and equipment failure in power system; these are the potential power quality problems. With the development of modern industry, many production processes and the assembly line (for example, semiconductor manufacturing, large-scale manufacturing, computer and paper enterprises etc.) rely on the equipment by computer chips or power electronic devices. Moreover, with the rapid growth of non-linear load or shock load applications, as well as the complex power system improve the increase fault, making people concerning to the power quality. These large-scale load input and system failures can cause a lot of power quality problems, such as the voltage sag, voltage surges, voltage imbalance, flicker, harmonics, and so on. These power quality problems on the production process and the process of assembling an adverse effect: to reduce the quality of products, interruption of production processes, and cause great economic losses [4].

Description of Voltage Sags

Voltage sags are momentary dips in voltage with a magnitude of 0.9 p.u. or below and duration between half a cycle to 1 minute. It is recognized as the most important power quality problem affecting industrial customers because it may cause sensitive equipment like adjustable speed drives and programmable logic controllers to trip, thus affecting industrial production losses. Such occurrences have major economic impact as well as impact on the quality of products or services [2].

Harmonic

The typical definition for a harmonic is “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency.” Some references refer to “clean” or “pure” power as those without any harmonics. But such clean waveforms typically only exist in a laboratory. Harmonics have been around for a long time and will continue to do so. In fact, musicians have been aware of such since the invention of the first string or woodwind instrument. Harmonics (called “overtones” in music) are responsible for what makes a trumpet sound like a trumpet, and a clarinet like a clarinet. Electrical generators try to produce electric power where the voltage waveform has only one frequency associated with it.[5].

Total Harmonic Distortion (THD)

THD is defined as the RMS value of the waveform remaining when the fundamental is removed. A perfect sine wave is 100%, the fundamental is the system frequency of 50. Harmonic distortion is caused by the introduction of waveforms at frequencies in multiplies of the fundamental i.e.: 3rd harmonic is 3x the fundamental frequency / 150Hz. Total harmonic distortion is a measurement of the sum value of the waveform that is distorted. Harmonic problems are almost always introduced by the consumers’ equipment and installation practices. Harmonic distortion is caused by the high use of non-linear load equipment such as computer power supplies, electronic ballasts, compact fluorescent lamps and variable speed drives etc., which create high current flow with harmonic frequency components [8].

Flexible AC Transmission Systems (FACTS)

Flexible ac transmission systems, called FACTS, got in the recent years a well-known term for higher

controllability in power systems by means of power electronic devices. Several facts-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice. In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines.

Facts-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations [7]. The basic applications of facts-devices are: Power flow control, Increase of transmission capability, Voltage control, Reactive power compensation, Stability improvement, Power quality improvement, Power conditioning, Flicker mitigation, Interconnection of renewable and distributed generation and storages [9].

Table 1: Overview of Basic Devices (FACTS & D-FACTS (CPD))

	Flexible AC Transmission (FACTS)		Costume Power Device D-FACTS (CPD)
Types of Connection	Thyristorvalve	VSC	Compensating Type
Shunt	Static Var Compensator (SVC)	Static Compensator (STATCOM)	Distribution Static Compensator (D-STATCOM)
Series	Thyristor Controlled Series Capacitor (TCSC)	Static Synchronous Series Compensator (SSSC)	Dynamic Voltage Restorer (DVR)
Shunt-Series	Dynamic Power Flow Controller (DPFC)	Unified Power Flow Controller (UPFC)	Unified Power Quality Conditioner (UPQC)

LCL Filters

Generally, LCL filter is used to interconnect a power electronic converter to a grid system. By using an LCL filter, high attenuation of harmonics caused by the PWM and high dynamic performance can be obtained simultaneously. Nevertheless, designing an LCL filter is not simple because of high compensating bandwidth and variable frequency modulation involved in active filter. In recent year, the voltage-source Inverter (VSI) is often used in regenerative energy systems and energy storage systems. In this application, power regeneration, adjustable power factor and reduced current harmonic distortion are the most important factor. Moreover, VSI based active rectifier represents an attractive solution due to the possibility to obtain sinusoidal output current with a Total Harmonic Distortion below 5%(e.g. IEEE-519- 1992).

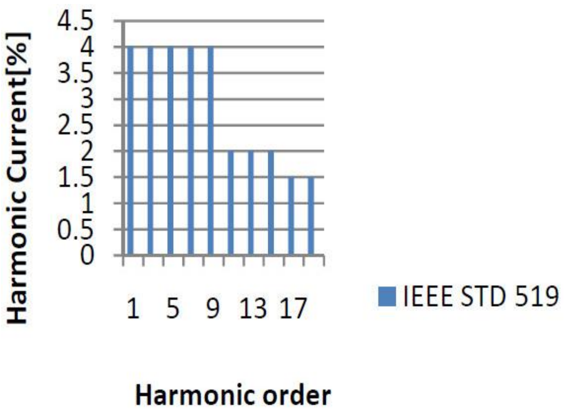

Figure 1: IEEE STD 519-1992 of Current Harmonic Spectrum

MATERIALS AND METHODS

Distribution Static Compensator (D-STATCOM)

A D-STATCOM consists of a two-level VSC, a dc energy storage device, controller and a coupling transformer connected in shunt to the distribution network. Figure 2 shows the schematic diagram of D-STATCOM.

$$Iout = IL - IS = IL - \frac{Vth - VL}{Zth} \tag{3.1}$$

$$Iout < \gamma = IL < (-\theta) - \frac{Vth}{Zth} < (\gamma - \beta) + \frac{Vth}{Zth} < (-\beta) \tag{3.2}$$

Iout = output current, IS =source current, IL =load current, VL =load voltage, Vth =Thevenin voltage, Zth =impedance

Referring to the equation 3.2, output current, *Iout*will correct the voltage sags by adjusting the voltage drop across the system impedance, (**Zth=*R+jX***). It may be mention that the effectiveness of D-STATCOM in correcting voltage sags depends on:

- The value of Impedance, **Zth= *R+jX***b) The fault level of the load bus

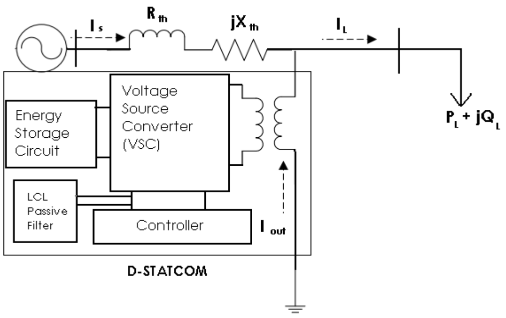

Figure 2: Schematic Diagram of a D-STATCOM

Voltage Source Converter (VSC)

A VSC is a power electronic system which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. It could be a 3 phase - 3 wire VSC or 3 phase - 4 wire VSC. Either a conventional two level converter or a three level converter is used. In propose D-STATCOM we used IGBT switching. A voltage-source converter connected in shunt or parallel to the system. It can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. The VSC used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual. It also converts the DC voltage across storage devices into a set of three phase AC output voltages [6].

Energy Storage Circuit

DC source is connected in parallel with the DC capacitor. It carries the input ripple current of the converter and it is the main reactive energy storage element. This DC capacitor could be charged by a battery source or could be recharged by the converter itself.

LCL Passive Filter

Commonly a high-order LCL filter has been used in place of the conventional L-filter for smoothing the output

currents from a VSI. The LCL filter achieves a higher attenuation along with cost savings, given the overall weight and size reduction of the components. LCL filters have been used in grid-connected inverters and pulse-width modulated active rectifiers. Because they minimize the amount of current distortion injected into the utility grid, Good performance can be obtained in the range of power levels up to hundreds of kW, with the use of small values of inductors and capacitors. The following per-phase equivalent model has been fully described in an earlier paper written by the authors. The LCL filter model is shown in Figure 3

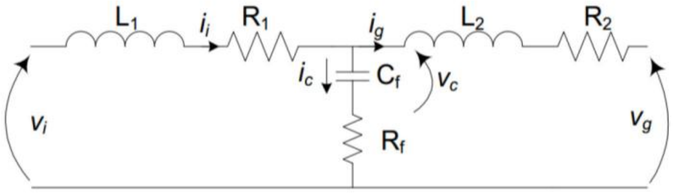

Figure 3: LCL Filter Model

Table 2: List and Value of Parameters Used in Simulation

Symbol	**Name**	**Quantity Value**	**Cf**	**Filter Capacitance**	**0.0012 uF**
*E*n	RMS value of grid voltage	11kV (rms)	*R*f	Resistance of converter-side filter	15 Ω
*f*n	Grid frequency	50 Hz	*R1*	Grid-side filter Resistance	5 Ω
i ripm	15% of peak value fundamental Harmonic current	582mA (rms)	*R2*	Converter-side filter Resistance	5 Ω
L1	Grid-side filter inductance	150 mH	*f*sw	Switching frequency	20kHz
L2	Converter-side filter inductance	75 mH	*f*res	Resonance frequency	5.25 kHz

PI Controller

In Proportional Integral mode, the controller makes the following: Multiplies the Error by the Proportional Gain (Kp) and Added to the Integral error multiplied by Ki, to get the controller output. In the next figure we show an example of a P controller with different Proportional Gains. The integral term (when added to the proportional term) accelerates the movement of the process towards set point and eliminates the residual steady-state error that occurs with a proportional only controller. However, since the integral term is responding to accumulated errors from the past, it can cause the present value to overshoot the set point value (cross over the set point and then create a deviation in the other direction).

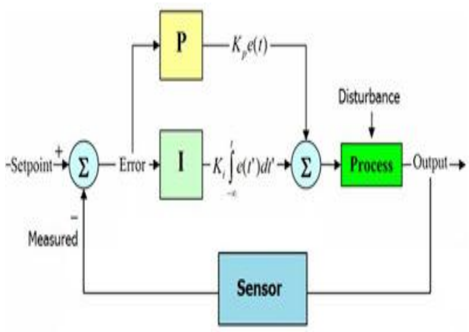

Figure 4: PI Controller Block Diagram

PWM

PWM generator is the device that generates the Sinusoidal PWM waveform or signal. To operate PWM generator, the angle is summed with the phase angle of the balance supply voltages equally at 120 degrees. Therefore, it can produce the desired synchronizing signal that required. PWM generator also received the error signal angle from PI controller. The modulated signal is compared against a triangle signal in order to generate the switching signals for VSC valves [62].

System Test

The test system shown in Figure 5 comprises a 33kV, 50Hz transmission system, represented by a Thevenin equivalent, feeding into the primary side of a 3-winding transformer connected in Y/Y/Y, 33/11/11 kV. A varying load is connected to the 11kV, secondary side of the transformer. A two-level D-STATCOM is connected to the 11kV tertiary winding to provide instantaneous voltage support at the load point. A 650 μF capacitor on the DC side provides the D-STATCOM energy storage capabilities. Breaker 1 is used to control the period of operation of the D-STATCOM and breaker 2 is used to control the connection of load 1 to the system.

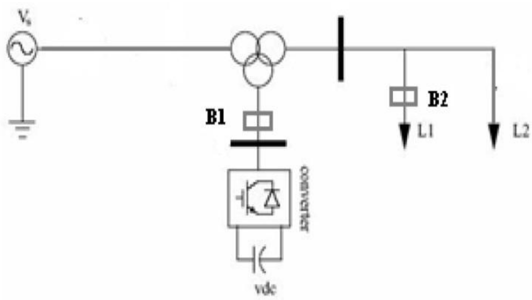

Figure 5: Single Line Diagram of the Test System

Simulink Model for the Test System

The test system was design using MATLAB Simulink is shown in figure 6 below

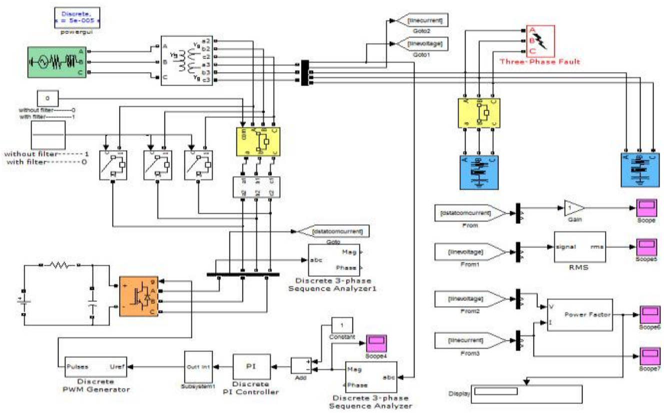

Figure 6: Simulink Diagram of the Test System

RESULTS AND DISCUSSIONS

To create distortion in the distribution system, different types of fault such as Three Line to Ground (TLG), Double Line to Ground (DLG), Line to Line (LL), and Single Line to Ground (SLG) are injected.

Voltage without Insertion of D-STATCOM

Table 3: Results of Voltage Sags for Different Types of Fault without D-STATCOM

Fault Resistance Rf,Ω	Voltage Sags for TLG Fault (p.u)	Voltage Sags for DLG Fault (p.u)	Voltage Sags for LL Fault (p.u)	Voltage Sags for SLG Fault (p.u)
0.6	0.6296	0.6820	0.7388	0.8123
0.7	0.6803	0.7237	0.7719	0.8530
0.8	0.7270	0.7625	0.8035	0.8563
0.9	0.7678	0.7971	0.8327	0.8756

Table 3 shows the overall results of voltage sags in p.u for different types of fault. From the table, it can be observed that when the value of fault resistance is increase, the voltage will also increased for different types of fault.

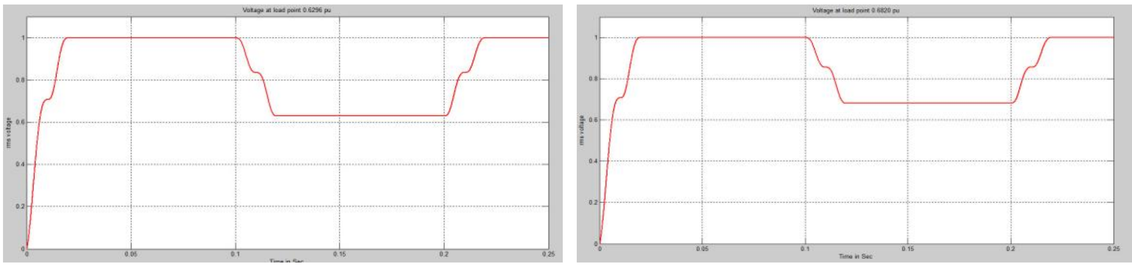

Figure 7: (A), (B) Voltage at Load Point is 0.6296 P.U TLG, 0.6820 P.U DLG

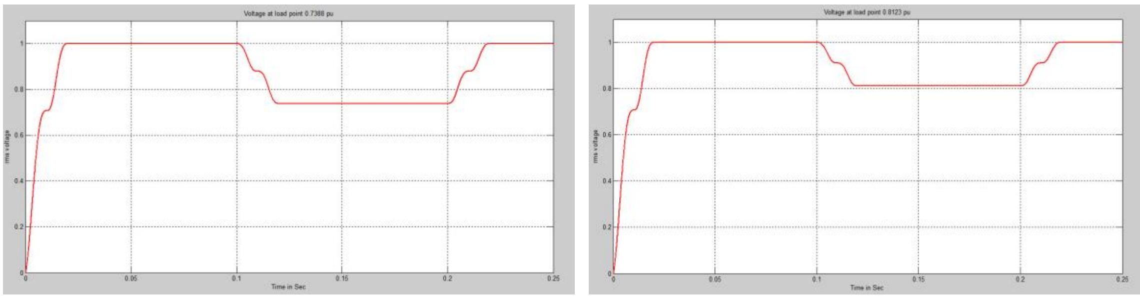

Figure 7: (C), (D) Voltage at Load Point is 0.7388 P.U LL, 0.8123 P.U SLG

Figures7 (A) to 7 (D) show the simulation results of the test system for different types of fault. The fault occur during (100-200ms) when the fault resistance, Rf =0.6 Ω.

Voltage with Insertion of D-STATCOM

Table 4: Results of Voltage Sags for Different Types of Fault with D-STATCOM

Fault Resistance Rf,Ω	Voltage Sags for TLG Fault (p.u)	Voltage Sags for DLG Fault (p.u)	Voltage Sags for LL Fault (p.u)	Voltage Sags for SLG Fault (p.u)
0.6	0.9317	0.9796	1.0184	0.9849
0.7	0.9400	0.9802	1.0158	0.9829
0.8	0.9487	0.9827	1.0146	0.9835
0.9	0.9580	0.9879	1.0156	0.9881

Table 4 shows the overall results of voltage sags in p.u with different types of fault. From the table, it can be observed that voltage sags improved with insertion of D-STATCOM. The value of voltage sags is between (0.9317 to 1.0184 p.u.).

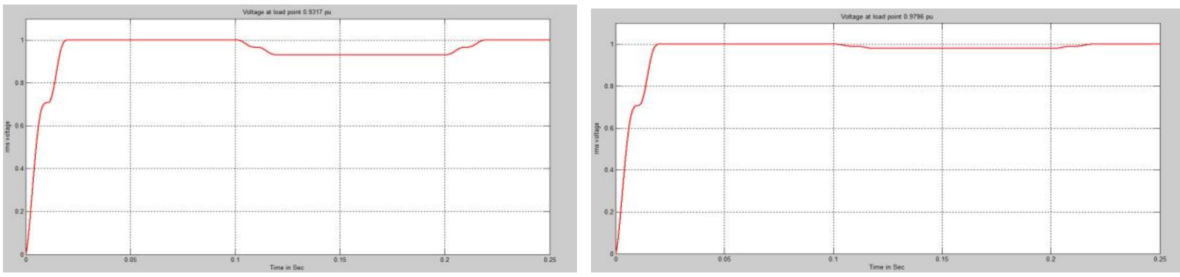

Figure 8: (A), (B) Voltage at Load Point is 0.9317 P.U TLG, 0.9796 P.U DLG

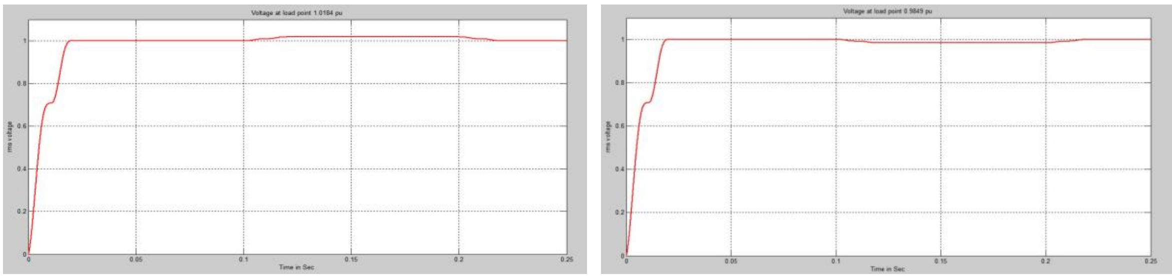

Figure 8: (C), (D) Voltage at Load Point is 1.0184 P.ULL, 0.9849 P.USLG

Figure 8 (A) to 8 (D) show the simulation results of the test system for different types of fault. The fault occurs during (100-200ms) when the fault resistance is 0.6 Ω.

Current Waveform without LCL Filter

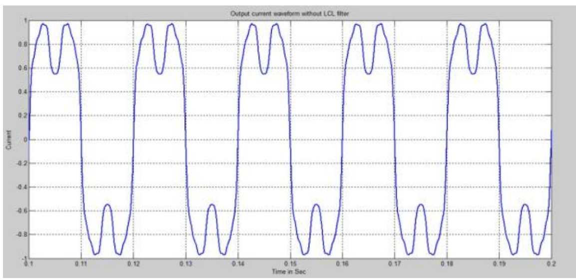

Figure 9: Waveform of Distortion Output Current without LCL Filter

Figure 9, shows the waveform of distortion output current without LCL Filter

Table 5: Results of Current Harmonic for Different Types of Fault without LCL Filter

Number of Harmonic Spectrum	1st	3rd	5th	7th	9th	11th	13th	15th	17th	19th	THD	Power Factor
Harmonic Distortionof 0.8 **TLG** Fault %	100.00	61.75	1.97	13.43	5.99	1.21	5.29	0.84	1.75	1.90	63.63	0.84
Harmonic Distortion of 0.8 **DLG** Fault %	100.00	86.10	1.84	17.38	8.53	2.95	6.92	0.74	2.83	2.53	88.68	0.75
Harmonic Distortion of 0.8 **LL** Fault %	100.00	42.73	1.54	10.27	5.00	2.09	3.55	0.61	1.71	1.33	44.52	0.91
Harmonic Distortion of 0.8 **SLG** Fault %	100.00	47.22	1.72	8.28	3.56	0.95	3.36	0.60	1.14	1.24	48.27	0.90

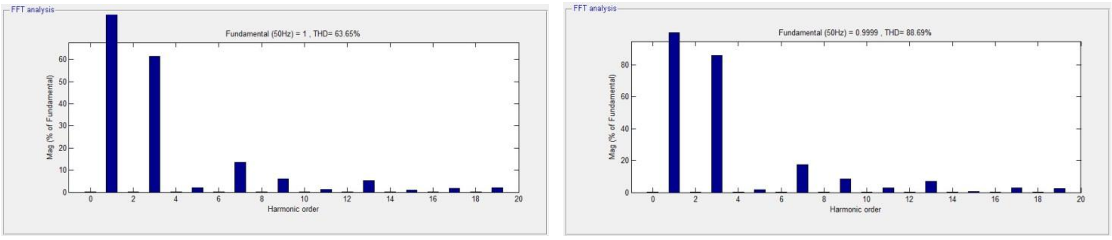

Figure 10: (A), (B) Harmonic Spectrum of Distortion Output Current without LCL Passive Filter of 0.9 TLG Fault, 0.9 DLG Fault

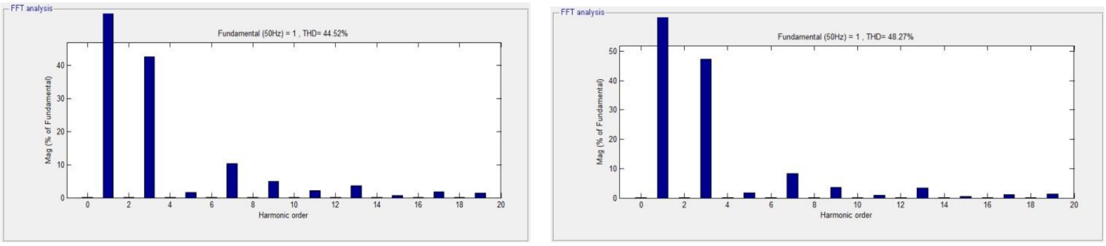

Figure 10: (C), (D) Harmonic Spectrum of Distortion Output Current without LCL Passive Filter of 0.9 LL Fault, 0.9 SLG Fault

Current Waveform with LCL Filter

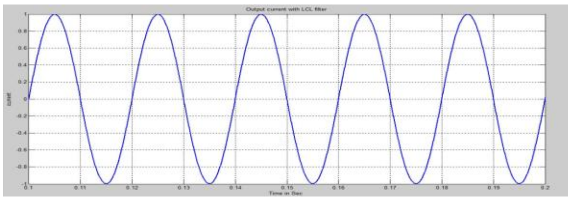

Figure 11: Waveform of Output Current with LCL Filter

Figure 11 shows waveform of sinusoidal output current with LCL Filter.

Table 6: Results of Current Harmonic for Different Types of Fault with LCL Filter

Number of Harmonic Spectrum	1st	3rd	5th	7th	9th	11th	13th	15th	17th	19th	THD	Power Factor
Harmonic Distortion of 0.8 **TLG** Fault %	100.00	0.81	0.41	0.29	0.23	0.19	0.16	0.14	0.12	0.11	1.12	0.99
Harmonic Distortion of 0.8 **DLG** Fault %	100.00	0.81	0.42	0.30	0.24	0.19	0.16	0.14	0.12	0.11	1.12	0.99
Harmonic Distortion of 0.8 **LL** Fault %	100.00	0.43	0.16	0.13	0.13	0.08	0.07	0.05	0.05	0.04	0.66	0.99
Harmonic Distortion of 0.8 **SLG** Fault %	100.00	0.82	0.42	0.32	0.28	0.20	0.17	0.14	0.12	0.11	1.14	0.99

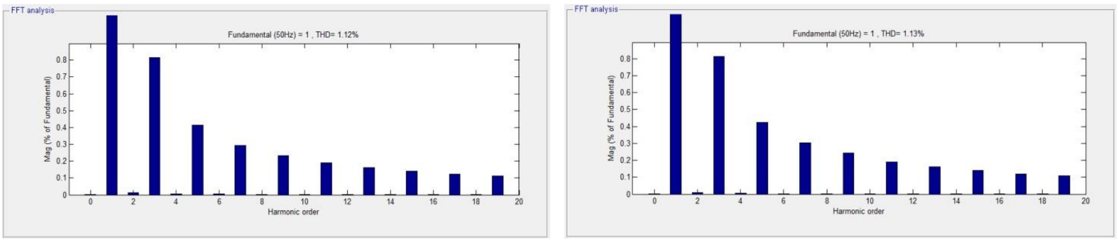

Figure 12: (A), (B) Harmonic Spectrum of Distortion Output Current with LCL Passive Filter of 0.9 TLG Fault, 0.9 DLG Fault

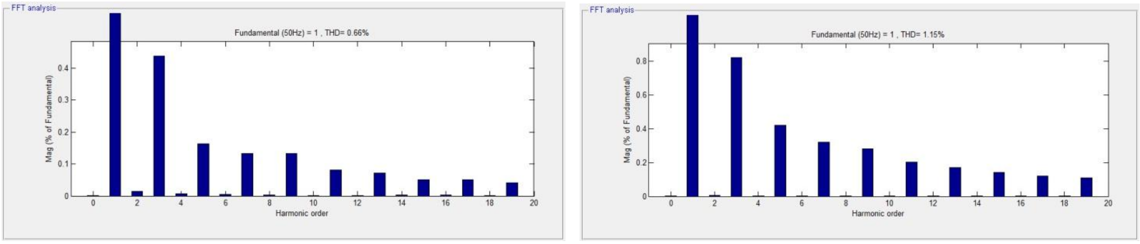

Figure 12: (C), (D) Harmonic Spectrum of Distortion Output Current with LCL Passive Filter of 0.9 LL Fault, 0.9 SLG Fault

CONCLUSIONS

The simulation results show that the voltage sags can be mitigate by inserting D-STATCOM to the distribution system. By adding LCL Passive filter to D-STATCOM, the THD reduced within the IEEE STD 519-1992. The power factors also increase close to unity. Thus, it can be concluded that by adding D-STATCOM with LCL filter the power quality is improved.

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AUTHOR'S DETAILS

Er. Firas Marwan Fakhraldin has done his B.Tech degree in Electrical Engineering from University of Mosul, Mosul, Iraq, and his M.Tech degree in Electrical Engineering (Power Systems) from SHIATS, Allahabad, UP, India. He is working as Senior Engineer in General Directorate of North Distribution Electricity, Ministry of Electricity, Iraq. He has several international papers to his credit. His field of interest and research is Distribution System. His research aims to improve power quality in distribution system.

Dr. Jyoti Shrivastava has done her graduation in Electrical Engineering and her post graduation in Design of Heavy Electrical Equipments. At present she is serving as a Senior Assistant Professor in Electrical Engineering department at college of Engineering and Technology, SHIATS, Allahabad, India. She has several international and National papers to her credit. Her field of interest and research are Power system control and operation, power quality improvement and condition monitoring of heavy electrical equipments. Her research aims to increase Transmission & Distribution system capacity and enhancing system reliability.

Dr. Mohammed Ramiz Almallah has done his B.Tech, M.Tech, Ph.D degree in Electrical Engineering from University of Mosul, Mosul, Iraq, He is working as Chief Engineer in General Directorate of Electricity/Northern, Ministry of Electricity, Iraq. He has several national and international papers to his credit. His field of interest and research is Transmission System.

Er. Israa Tawfik Aziz has done her B.Tech degree in Computer Engineering from University of Mosul, Mosul, Iraq, and her M.Tech degree in Computer Science Engineering from SHIATS, Allahabad, UP, India. She is working as Assistant Engineer in College of Science, University of Mosul, Ministry of Higher Education, Iraq. She has several international papers to her credit.